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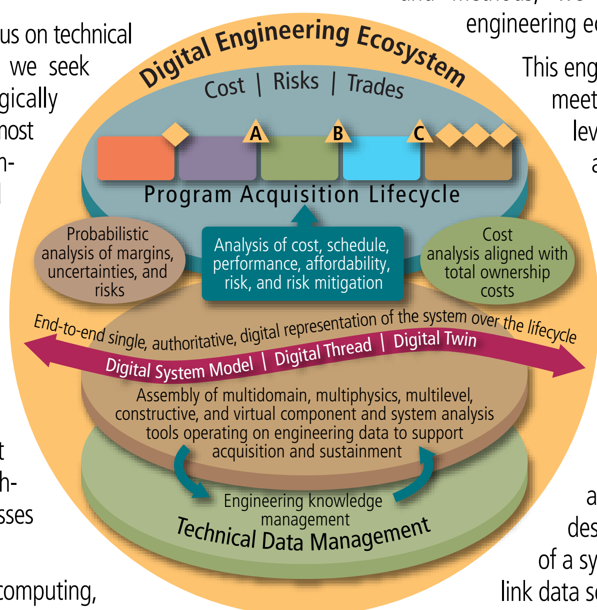
MODEL-BASED SYSTEMS ENGINEERING: ENABLING THE DIGITAL ENGINEERING PRACTICE IN THE DEPARTMENT OF DEFENSE

By KRISTEN BALDWIN, Acting Deputy Assistant Secretary of Defense for Systems Engineering

As engineers, we focus on technical excellence. In DOD, we seek to deliver technologically superior capabilities, most of which involve complex integrated and networked systems that serve a diverse range of missions and users. We balance the challenge of designing and delivering complex systems with other challenges, including a changing threat environment, fierce competition for talent and resources, the rapid pace of commercial technology and innovation, and risk-averse processes and infrastructure.

At the same time, however, advancements in computing, modeling, data management, and analytical capabilities offer great opportunity to engineering practice. Applying these tools and methods, we are shifting toward a dynamic digital engineering ecosystem.



Holistic view of digital engineering support to DOD acquisition. [Illustration courtesy DOD, used with permission.]

This engineering transformation is necessary to meet new threats, maintain overmatch, and leverage technology advancements. As articulated by Stephen Welby, Assistant Secretary of Defense for Research and Engineering, in an interview posted on SpaceWar.com in August 2016, "To surf the wave of global innovation, we must paddle out in front."

Digital engineering will involve adopting an integrated model-based engineering approach through the use of digital environments, processes, methods, tools, and digital artifacts to support the planning, design, validation, operation, and sustainment of a system. A digital engineering ecosystem will link data sources and models across stakeholders throughout the lifecycle. It will provide the authoritative source of truth. Knowledge and rationale for changes will be maintained; knowledge will not be just shared, but will be the cohesive

continued on page 3

LESSONS LEARNED: SATELLITE BREAKUP—ATTITUDE CONTROL SUBSYSTEM NEEDS A SANITY CHECK

By DAVIN K. SWANSON
The Aerospace Corporation

In 2016, spacecraft operators permanently lost contact with a science satellite only a month after launch. The subsequent investigation revealed that a series of poor design decisions and human errors caused the spacecraft to spin up uncontrollably, which led to structural failure and total loss of the satellite.

The satellite's onboard attitude determination system relies on a Kalman filter, which combines measurements from various sensors (such as gyros and star trackers) to obtain an estimate of the vehicle's orientation. When the satellite entered the South Atlantic Anomaly, an area of increased radiation, the system disabled use of potentially invalid star tracker measurements, relying solely on gyro measurements to propagate its attitude.

Due to an aggressive selection of initial Kalman filter parameters and high initial estimate errors, the estimate of the gyro bias had large errors during this phase, causing the satellite to rotate at

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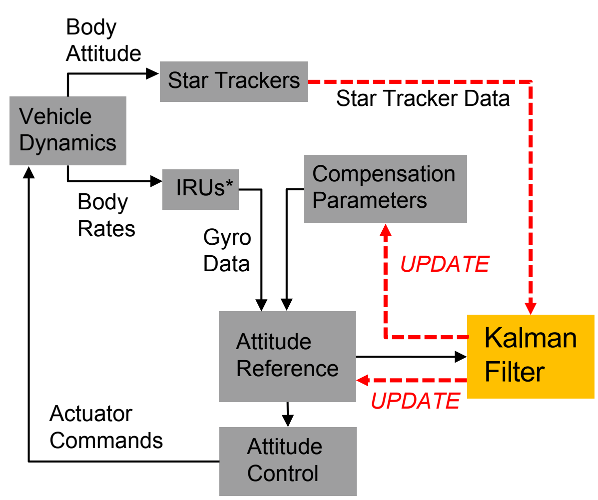

Without star tracker measurements, compensation parameters were not corrected appropriately, causing errors in the attitude reference.

** inertial reference units*

IMPROVING EFFICIENCY IN AI&T

By JEFF JURANEK AND CHARLES WRIGHT
The Aerospace Corporation

Assembly, integration, and test (AI&T) often gets the blame for schedule and cost increases—but is this blame really justified? The Aerospace Corporation conducted a study to understand why major schedule increases occur on space vehicles during the AI&T phase. The study suggests problems can be traced back to poor schedule realism, design escapes, workmanship issues, late deliveries, and thermal vacuum retesting.

Analysts reviewed timelines and problem areas across 20 early-build space vehicles (defined as the first three vehicles in a block build). All programs, with the exception of one, experienced schedule overruns. These overruns and extensions collectively translate to a significant amount of unplanned work and demonstrated that AI&T schedules are routinely unexecutable for early-build vehicles.

Detecting and correcting design defects early in a product lifecycle has become difficult as space systems become more complex. Design review processes sometimes fail to identify issues early in the development phase and result in design escapes discovered during AI&T with unplanned schedule extension. While design review processes are well documented and time proven, late design changes indicate a process gap. Research identified that many design escapes are preventable with the right set of subject matter experts using a robust process, including performing incremental reviews.

Workmanship issues can flow into AI&T from manufacturing and the supply chain. Strong supply chain management controls are required to ensure the quality of the delivered product. Using error-proofing techniques in designs is just one method for reducing workmanship issues and unplanned work.

Design escapes, workmanship issues, and late delivery of hardware/software/ground support equipment drive inefficiencies during the AI&T phase. Finding design and workmanship problems before the hardware is integrated into the vehicle is a key driver of efficiency in AI&T. Improved unit design rigor and workmanship screening prevents passing defective hardware downstream.

When the focus is on reducing cycle time in AI&T, eliminating environmental tests or the number of test cycles is the typical target. While these approaches may make sense for well-established designs, they can increase mission risk for early-build vehicles. Research has shown: Testing is not the problem—waste is.

Significant amounts of waste exist in AI&T: Errors in procedures, test setup/facility discrepancies, and test software database errors contribute to poor schedule performance and overall inefficiency. Delays, idle time, and equipment downtime also contribute to inefficiency. A preferred approach to reduce cycle time is to use industrial engineering methods and lean techniques to target waste. Value stream mapping, process failure modes-and-effects analysis, and discrepancy metrics are effective tools used to optimize the space vehicle AI&T process.

There are heavy schedule impacts to AI&T when thermal vacuum testing has to be repeated. Part of this study reviewed 29 space vehicles since 2000. Of these, 11 (or 38%) saw one to three additional thermal vacuum tests in AI&T for a total of 16 retests. Assuming an additional 40 days for each one, it's clear that these retests consumed a significant amount of time and effort. To address this industrywide issue, Aerospace and industry contractors have

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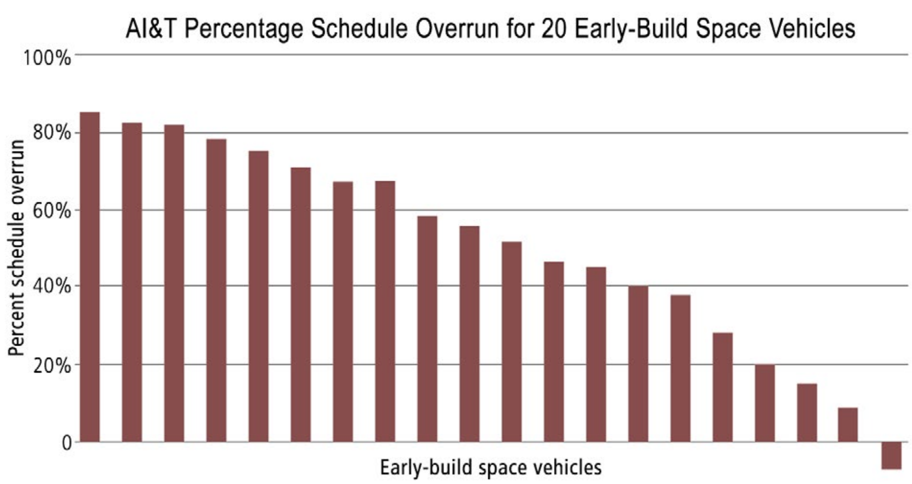


Program schedule analysis highlighting percentage schedule overruns, based on the planned vs. actual durations for AI&T (this chart assumes a six-day nominal workweek, except for thermal vacuum testing, which runs continuously until complete).

CHIEF ENGINEER'S CORNER

William Tosney
General Manager and
Corporate Chief Engineer

We are witnessing history every day: Innovative applications of new technologies, a crush of entrepreneurs willing to take risks—that's the space industry we find ourselves in today. This is reminiscent of the situation in the 1990s, when many new technological and business approaches were attempted—and typically without success.

But technologies have matured more today, and affordable access to space is becoming a reality. We have also learned to better infuse newly gained knowledge into our best practices. We assiduously push product advancements, together with process improvements, into our systems to strive for enhanced performance. Never settling for "good enough" is what allows us to keep our technological edge—despite a sometimes fragile industrial base—to counter increased threats.

Through it all, mission assurance core tenets continue to prove their ability to accommodate growing demands for faster technology insertion, greater emphasis on mission systems engineering, and a broader emphasis on resilience in space and on the ground.

Striving for greater efficiency and effectiveness is an ever-critical challenge as we balance resources in the pursuit of mission goals. Getting it right the first time is predicated on disciplined engineering, skilled project management, and—more often than we care to admit—learning from other people's mistakes.

DID YOU KNOW…?

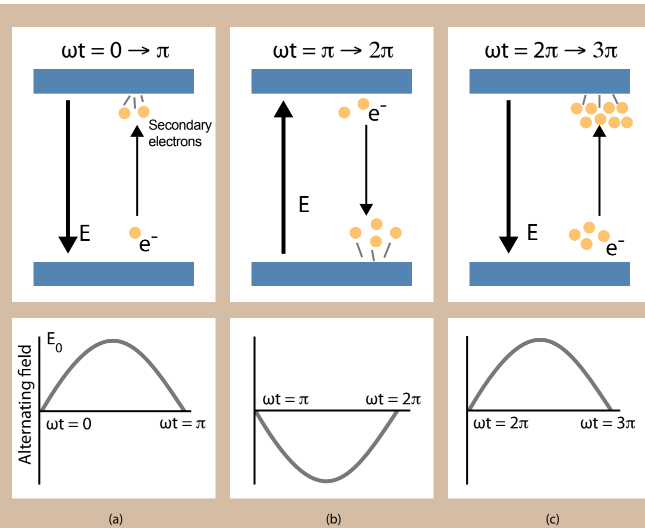
Beware of RF Breakdown

The American Institute of Aeronautics and Astronautics (AIAA) recently adopted *Standard/Handbook for Multipactor Breakdown Prevention in Spacecraft Components* as ANSI/AIAA S-142-2016. Multipactor—a form of radio frequency (RF) breakdown—occurs in a vacuum when free electrons are accelerated in the presence of an RF electric field. The subsequent collisions with material surfaces can generate more electrons with each surface impact. This can quickly develop into a device-damaging plasma.

Multipactor can limit or permanently degrade RF/microwave components such as high-power amplifiers, isolators, switches, filters, antenna feeds, and others. These components are critical for communication and navigation satellites.

The new AIAA standard provides an entirely new process to prevent RF breakdown early in the design and production phases. New analysis and test methods identify problems early, preventing expensive failures late in production or on orbit.

The standard establishes new bounding processes that enable programs to confidently remove excess margin from their designs, which can result in large cost savings. The standard also introduces numerical analysis techniques that can, in certain cases, eliminate the need for expensive qualification and acceptance testing. It recommends methods, with examples, to ensure proper requirement verification for all satellite components susceptible to RF breakdown.



Above: Multipactor breakdown occurs when electrons are accelerated in the presence of an alternating RF field in vacuum. The collisions can free up more electrons in a cascade reaction, forming an energetic plasma.

A second standard focusing on a related phenomenon known as ionization breakdown is also under development.

For more information, contact Timothy Graves, 703.808.6159, ***timothy.p.graves@aero.org****.*

MODEL-BASED SYSTEMS ENGINEERING

continued from page 1

entity that keeps all aspects of a system lifecycle together.

This evolutionary concept is not new, but demand and technology have advanced to a point where the return on investment is unquestioned. Many organizations, labs, and programs in government and industry are incorporating digital engineering practices. Collaboration will be a key attribute in making a complete transition.

Within DOD and with the defense industrial base we have identified pathfinders and developed structured mechanisms to exchange practices. Shared interest in model-based systems engineering among federal agencies has led to joint activities to define and explore digital engineering interests. DOD and NASA are teaming to apply and assess digital engineering practices on a NASA program to understand program management integration. These activities provide important pathfinders and lessons learned.

Education is also important. DOD is developing policy and guidance for digital, model-based engineering, and has begun modifying the systems engineering curriculum to update the vernacular and increase the common understanding of digital engineering concepts. No change is possible without a knowledgeable workforce.

Additionally, DOD is sponsoring systems engineering research to mature and incorporate advances in physics-based modeling, large tradespaces, and analytics into our engineering practices. This research is transitioning into military department and industry program applications.

These activities provide the foundation to transform not only engineering but the broader set of acquisition practices, impacting requirements, contracting, and program decisionmaking.

Change will be needed to cultural and historical business processes in addition to the engineering practice. However, if successful, we expect that digital, model-based practices will inform decisions through greater transparency and insight, enhance communication, provide understood flexibility and adaptability in designs, increase confidence in system performance, and improve efficiency.

In particular, they need to carefully examine the capture of requirements, the delivery of components and materials for fabrication, and the testing of fabricated parts.

Application of value stream mapping (figure on page 1) is one technique that can be used to identify risk touch points. It will improve our risk mitigation by addressing risk within the value stream of our own products as well as our suppliers and our suppliers' suppliers. Processes to resolve risk are unique to location in the value stream. These processes are designed to add value to ensure risk is fully mitigated. If value is defined as a process that a customer is willing to pay for, what innovations can be developed to optimize risk mitigation to make it affordable and effective?

Problems are generally easier and cheaper to fix when they are caught early (or prevented altogether). Proactive risk-management actions must be mandated and adequately funded. That could include the use of modeling and simulation early in development and the use of inline monitoring, rather than periodic audits, to uncover risks. It should also entail bringing the right subject matter experts into the risk mitigation process.

Ultimately, successful risk mitigation requires an experienced and knowledgeable staff. Industry and government should sponsor more joint education opportunities that bring together systems engineering, program management, and mission assurance personnel.

RECENT GUIDANCE AND RELATED MEDIA

Ground Segment Systems Engineering Handbook by G. Johnson-Roth et al.; TOR-2016-01797; OK'd for public release

Mission Assurance Across the Spectrum—White Paper by W. Tosney, G. Johnson-Roth; ATR-2016-03149; OK'd for public release

Acquisition Guidance for Affordability: Using Fixed-Price Contracts as a Contributing Tool for Successful Cost Control by S. Hastings et al.; TOR-2016-02779; OK'd for USG

Additive Manufacturing Mission Assurance Considerations by J. Nokes et al.; TOR-2016-02152; OK'd for public release

ASIC and FPGA Circuitware Development Benchmark for Mission-Critical Systems by C. Sather; TR-2016-02265-Rev A; OK'd for USGC

Application Specific Integrated Circuit (ASIC)/Field Programmable Gate Array (FPGA)/Non-Volatile Memory (NVM) Technology Study—2016 Update by D. Mayer et al.; TOR-2017-00297; OK'd for USG

Lessons Learned and Recommended Best Practices from Model-Based Systems Engineering (MBSE) Pilot Projects by R. Noguchi; ATR-2016-02309; OK'd for public release

Rationale for Requirements in SMC Standard SMC-S-011 (2015)—PMP Expendable Launch Vehicles by M. Garcia et al.; TOR-2015-03665; OK'd for USGC

Leveraging New Space by E. Swallow et al.; TOR-2016-03406; OK'd for USGC

Assembly, Integration and Test (AI&T) Efficiency Study by W. Tosney et al.; TOR-2016-01412; OK'd for USGC

Systems Engineering Forum: Model-Based Systems Engineering (MBSE) Focus Day by G. Johnson-Roth et al.; ATR-2017-00357; OK'd for public release

Leveraging MDA C2BMC Experiences in Support of the Space Enterprise Vision Battle Management Command and Control by C. Stevens et al.; ATR-2017-00493; OK'd for USGC

Stakeholder Review of Proposed New Standard: Evaluation and Test Requirements for Liquid Rocket Engines by K. Behring et al.; TOR-2017-00779; OK'd for USGC

Infant Mortality: Context and Definition by M. Cavanaugh et al.; TOR-2016-02811; OK'd for USGC

USG	U.S. Gov't Agencies
USGC	U.S. Gov't Agencies and Their Contractors

For reprints of these documents, except as noted, please contact ***library.mailbox@aero.org****.*

CALENDAR OF EVENTS

SPRING 2017

March 4–11 *IEEE Aerospace Conference, Big Sky, MT*

March 6–9 *Satellite 2017, Washington, DC*

March 7–9 *Goddard Memorial Symposium, Washington, DC*

March 13–14 *ASQ Collaboration on Quality in the Space and Defense Industries, Getting Ahead of the Curve—Prevention: Predictive, Proactive Tools and Techniques, Cape Canaveral, FL*

March 13–16 *21st Annual Ground System Architectures Workshop (GSAW), Los Angeles, CA*

March 14–15 *Quality Leadership Forum, Cape Canaveral, FL*

March 21–23 *Aerospace Testing Seminar (ATS) Technical Workshop, Los Angeles, CA*

March 23–25 *15th Annual Conference on Systems Engineering Research (CSER), Disciplinary Convergence: Implications for Systems Engineering Research, Redondo Beach, CA*

March 28–30 *Spacecraft Thermal Control Workshop, El Segundo, CA*

April 3–6 *33rd Space Symposium, Colorado Springs, CO*

April 4–5 *Space Parts Working Group Technical Workshop, Torrance, CA*

April 24–27 *Space Power Workshop, Manhattan Beach, CA*

April 25–27 *2017 AIAA Defense Forum, Laurel, MD*

May 2–4 *U.S. Space Program Mission Assurance Improvement Workshop, El Segundo, CA*

May 23–25 *Space Tech Expo USA, Pasadena, CA*

SUMMER 2017

June 20–22 *Spacecraft and Launch Vehicle Dynamic Environments Workshop, El Segundo, CA*

June 28–29 *MilSatCom USA, Arlington, VA*

July 17–21 *2017 IEEE Nuclear & Space Radiation Effects Conference, New Orleans, LA*

LESSONS LEARNED

continued from page 1

about 22 degrees/hour even though it was being commanded to remain stationary. The attitude control system tried to off-load momentum building up in the reaction wheels with magnetic torque rods, but the diverging attitude estimate caused this process to increase wheel speeds and eventually saturate them.

At this point the fault management system initiated sun safing on thrusters. However, thruster parameters that had been uploaded after launch contained several sign errors. It was found that the ground-based tool used for calculating these parameters had no configuration control, user's guide, or verification of its results. The sign errors caused the thrusters to spin up the satellite, leading to structural failure and vehicle break-up.

Lessons Learned

- The control system must check for excessive gyro drift during inertial sensor outages and appropriately swap hardware or enter a contingency mode instead of propagating the attitude.
- The control system should be designed to detect and mitigate anomalous thruster firings.
- Software that generates values uploaded to the satellite must be thoroughly verified.

Reference

Aerospace Report No. TOR-2016-02721.

For more information, contact Davin K. Swanson, 310.336.8795, ***davin.k.swanson@aero.org****.*

IMPROVING EFFICIENCY

continued from page 2

added thermal vacuum retesting to the 2017 Mission Assurance Improvement Workshop as a key focus area.

In today's cost-constrained acquisition environment, the need to make AI&T more efficient is crucial. AI&T efficiency can be improved by strengthening technical review processes to minimize design escapes, applying industrial engineering/lean methods to eliminate waste, and improving unit design rigor and workmanship screening to minimize late cycle escapes. The research conducted in this study will be beneficial to new programs that embed requirements to streamline the AI&T phase as well as existing programs to identify problems early.

Reference

Aerospace Report No. TOR-2016-01412.

For more information, contact Jeff Juranek, 310.336.3190, ***jeff.b.juranek@aero.org*** *or Charles Wright, 310.336.2259,* ***charles.p.wright@aero.org****.*

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